

MODULAR, RECONFIGURABLE, AND RAPID RESPONSE SPACE SYSTEMS: THE REMOTE SENSING ADVANCED TECHNOLOGY MICROSATELLITE

Jaime Esper*, Jim Andary, John Oberright, Maria So
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771

Peter Wegner, Alok Das
Air Force Research Laboratory/Space Vehicles Directorate, Kirtland AFB, New Mexico, 87117

Joe Hauser
Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375

ABSTRACT

Modular, Reconfigurable, and Rapid-response (MR²) space systems represent a paradigm shift in the way space assets of all sizes are designed, manufactured, integrated, tested, and flown. This paper will describe the MR² paradigm in detail, and will include guidelines for its implementation. The Remote Sensing Advanced Technology microsatellite (RSAT) is a proposed flight system *test-bed* used for developing and implementing principles and best practices for MR² spacecraft, and their supporting infrastructure. The initial goal of this test-bed application is to produce a lightweight (~100 kg), production-minded, cost-effective, and scalable remote sensing micro-satellite capable of high performance and broad applicability. Such applications range from future *distributed space systems*, *to sensor-webs*, and *rapid-response satellite systems*. Architectures will be explored that strike a balance between modularity and integration while preserving the MR² paradigm. Modularity versus integration has always been a point of contention when approaching a design: whereas one-of-a-kind missions may require close integration resulting in *performance optimization*, multiple and flexible application spacecraft benefit from modularity, resulting in *maximum flexibility*. The process of building spacecraft rapidly (< 7 days), requires a concerted and methodical look at system integration and test processes and pitfalls. Although the concept of modularity is not new and was first developed in the 1970s by NASA's Goddard Space Flight Center (Multi-Mission Modular Spacecraft), it was never modernized and was eventually abandoned. Such concepts as the Rapid Spacecraft Development Office (RSDO) became the preferred method for acquiring satellites. Notwithstanding, *over the past 30 years technology has advanced considerably*, and the time is ripe to reconsider modularity in its own right, as enabler of R², and as a key element of transformational systems. The MR² architecture provides a competitive advantage over the old modular approach in its rapid response to market needs that are difficult to predict both from the perspectives of evolving technology, as well as mission and application requirements.

Keywords: Modular, plug-and-play, reconfigurable, responsive.

INTRODUCTION

The NASA Goddard Space Flight Center (GSFC), in collaboration with government and industry partners, is currently working to develop a paradigm shift in the way space systems are put together. Revolutionary transformational improvements in the design, architecture, and processes involved in the

production of current flight systems (hardware and software) are essential to achieving the goals set forth in the President's new Vision for NASA, and critical across-the-board in any space-bound exploratory, scientific, or commercial endeavor. This paper will introduce the concept of MR², and describe in some detail a proposed new spacecraft built under its paradigm. In addition to NASA's work on MR², the Air Force Research Laboratory/Space Vehicles

* Email: Jaime.Esper@nasa.gov; Telephone: (301) 286-1124; Fax: (301) 286-0886

Directorate (AFRL/VS) in Albuquerque is also embarked in research leading to responsive space systems, as is the Naval Research Laboratory (NRL) in Washington, DC. The motivation from a military point of view is clear. The mutual NASA/DoD interest in responsive systems has to do with process improvements in the mission life cycle. As schedules get compressed and new processes are adopted, costs are bound to decrease. This assumes an operational system and MR² paradigm shift that has been proven over a series of flights.

DEFINITIONS

Definitions are important for providing the context on which to base the current development. Each term of MR² is defined in turn.

Modular

MR² systems contain selectable electro-mechanical and software components that may be re-used in quantized numbers. The system must be capable of evolving to incorporate advances in technology, and it must accept standard interfaces and plug-and-play principles (e.g. Personal Computers). Collectively (and possibly individually) must result in intelligent units. This last item refers to the ability to assemble a larger system on-orbit from a number of individual intelligent units. It is reasonable to assume that modularity is the basis for both re-configurability and responsiveness, as defined next.

Reconfigurable

The system must be capable of morphing in order to apply to a host of missions, it must be easy to produce, integrate, test, and launch, and it must be capable of operating alone or as a collective part, physically detached or attached.

Rapid

The time lapse from requirements definition to launch must range from days (< 7), to months (< 12), depending on application and needs. Although this definition is decidedly geared toward smaller space assets, large space systems may equally benefit from life-cycle process improvements.

MR² and RSAT: a means to a new beginning

MR²: A Modular, Reconfigurable, and Rapid Response *Space System Architecture*. This refers to a paradigm shift in the way space systems (from spacecraft to ground systems and operations) are conceptualized and implemented.

RSAT: Remote Sensing Advanced Technology Micro-Satellite - MR²'s proposed *Flight Test-Bed*.

MR² spacecraft are resource scalable, i.e., mass, power, and volume may vary depending on application and needs.

It should be noted that although a spacecraft does not necessarily need to be reconfigurable to be responsive (multiple copies on a shelf), the power that MR² brings to the table is in its ability to generate spacecraft that can morph to attain varying mission objectives on short notice, or with maximum re-use of modular components.

BROAD OBJECTIVES OF MR²

The design paradigm embodied in MR² is applicable to small and large spacecraft alike. As there is a desire to develop high performing capabilities in smaller packages, the *initial* goal of MR² is the creation of a micro-satellite which will serve as its paradigm's test-bed. MR² broad goals may be summarized as follows:

- Develop principles and best practices for modular (plug-and-play), reconfigurable, rapid-response, production-minded, and cost-effective space systems.
- Adopt a set of commercial mechanical, fluid, electrical, and software standard interfaces (modified as needed). Where appropriate, develop new interface standards.
- Study architectures using a blend of advanced technologies, plug-and-play modularity, and (where appropriate) subsystem integration. Technologies that support the MR² paradigm will be referred as "choice technologies" (*not* standard). They will be revised and updated on a recurring basis.
- Study system Integration and Test (I&T) processes and pitfalls involved in the production of advanced spacecraft on an accelerated schedule.
- Application of MR² principles to end-to-end space systems, instruments, UAVs, and other NASA and DoD assets.
- Develop an engineering process and a set of requirements that provide a consistent method for constructing systems under the MR² paradigm. This includes an analysis of acceptable and unacceptable risks based on purported application.

STRATEGIC OBJECTIVES OF MR² ON RESPONSIVE SPACE SYSTEMS

The rate of technology advancement and the proliferation of space technology around the world have increased at a rapid rate over the last 20 years. During that time period the US government has often become involved in small regional conflicts that can begin and end in less than six months. However, the time required for planning and conducting missions

in space has remained nearly constant. It often takes 10 years from the time a new space based capability is envisioned until the system is producing usable products. This means that space based capabilities are often not able to keep up with the progression of technology, nor with the changing political climate around the globe.

The US Department of Defense (DoD) desires to develop the technology necessary to eliminate this dichotomy. This technology would enable the DoD to conduct space missions in a very short time frame; from mission call to first returned product in less than one week. Further, this technology would enable these "responsive space capabilities" to rapidly adapt to changes in available technologies and to changing global conditions. To meet this aggressive goal it is believed that a MR² satellite architecture is required. It is envisioned that a series of small, rapidly reconfigurable satellites can be initially (but not exclusively) developed with this architecture. These satellites would be quickly interchangeable with payloads that would then be able to conduct a variety of space missions. It is believed that when applied to the proper set of missions, the MR² architecture will enable the DoD to maintain a competitive edge in the face of changing technologies and geo-political conditions.

Over the past ten years the Naval Research Laboratory has been involved in several studies designed to reduce the cost and schedule of spacecraft. A common theme to these efforts is the use of small, modular, reconfigurable satellites. The most recent study, conducted for the Office of Force Transformation (OFT), was tasked to evaluate launch and satellite options that could provide tactical forces with a "transformational" space-based capability. Here "transformational" was defined to mean, 'quick response, selectable (i.e. modular) payloads, low cost, and coverage of any location on earth at which a military conflict or interest arises'. The most recent study was driven by the DoD's belief that "responsive space access will be the key to augmenting communication networks, ISR coverage, and application of force from space over locations around the globe in a time-constrained environment." What the military envisions is a system of small, low cost, tactical satellites with payloads supporting the areas of networking, signals intelligence, communications, and imaging that can provide a quick & tailored response to conflicts. This certainly fits the rapid (or responsive) character contained within the MR² paradigm.

As a result of the OFT study, NRL was asked to develop a program that would result in the transformational capability described above. NRL proposed a progression of flight demonstrations that would validate key pieces of the planned system, each reducing risk and building on the previous one's successes. Each of these small, prototype tests would provide an operationally relevant capability that could be integrated into combatant commanders' exercises, and would also test out a concept of operations for the payload. *Modularity and re-configurability would be built into this spiral development so that the final result would be an MR²-like capability.*

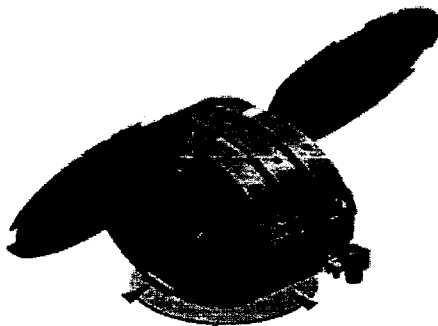
From a military standpoint, we see several key attributes that are provided by the MR² concept: it allows new war-fighting capabilities "on-demand"; it provides an efficient mechanism for fielding new technologies; it allows tactical control for quick deployment and assured access; it provides the capability to maximize coverage for a given area of interest (because it can be launched quickly after a new conflict arises); and it provides added deception capability. The similarities between the NASA MR² paradigm shift and the NRL 'transformational' program was recognized, and has resulted in the present collaboration.

NRL TACSAT 1

For the OFT program, NRL was designated as the program manager for the first demonstration satellite, dubbed Tactical Satellite-1 (TacSat-1). The purpose of TacSat-1 was to provide a credible concept and development approach as a starting point for a tactical micro-satellite program. The primary objectives for TacSat-1 were: fly militarily relevant payloads; low cost; short development time; and demonstrate how a warfighter could directly task and receive data over the SIPRNET (the military internet). All of these objectives will be met, in addition to demonstrating the capability to fly reconfigurable COTS parts not designed for space operation. Given its nature, TacSat-1 could very well be considered the first flight in this spiral development leading to MR²-enabled space systems. Figure 1a shows TacSat-1 on a sling on its way to undergo vibration testing. The spacecraft layout is shown in Figure 1b.



(a)



(b)

Figure 1: TacSat-1 readied for vibration testing (a), and on-orbit configuration (b).

As was stated earlier, over the past several years, NRL has undertaken many studies to look at MR²-like spacecraft, but they have not resulted in an actual program. What is different at this time, and why do we think it can work now? We believe that there have been significant advancements in technology that have resulted in large enough reductions in the size, weight and power of electronics, instruments, structures, power components, and mechanisms, that make a true MR² satellite possible. In fact, TacSat-1 and other small satellites have demonstrated that significant mission capability and autonomy is now possible with micro-satellites (<100kg), and MR² systems can continue to build on their foundation.

LONG TERM APPROACH

MR² is a system-level technology. As such, only component-level technologies that support the paradigm will be adopted, and new ones developed when required. The aim is to facilitate the infrastructure needed to further the paradigm shift, and not to develop the latest high-performance component technology. As rapid-response is an

essential element, the Goddard Space Flight Center's (GSFC) Integrated Mission Design Center (IMDC) has served as a laboratory for testing the flow and processes involved in MR². A number of point designs have been developed, and the Remote Sensing Advanced Technology (RSAT) micro-satellite is a good example. In the end, it is hoped that continuing progression through the TacSat series would yield a spacecraft much like RSAT. Hence, additional collaborative exercises between NASA and the DoD are expected.

A methodical look at each spacecraft architectural component has been undertaken to identify their ability to mold and morph under the new paradigm, while preserving a well-established interface. *Standard interfaces represent a key to ensuring compatibility of both hardware and software systems.* Mechanical, electrical, and software interface standards will be adopted that leverage multi-billion dollar investment ventures undertaken by private (non-aerospace) industry. Space-flight qualification of interfaces and components will be studied to ensure proper compatibility with stated MR² goals. The first NASA-sponsored workshop on interface standards was held at the Goddard Space Flight Center in February 2004. Co-hosted by JPL and Sponsored by NASA Headquarters Office of Exploration Systems, the workshop brought industry, academia, and government participation to a single forum. It is expected that such collaboration will continue with broad participation, including the DoD.

Product design and production techniques for space-bound systems will be developed to ensure compliance with the rapid character of MR². It is expected that MR² spacecraft will be optimized for application flexibility, and not for performance. Hence, from a system perspective, there will be mass, power, and volume penalties. Given this, it is recognized that certain mission classes may require a performance optimization that can only be achieved through the use of one-of-a-kind systems. Outer planetary missions, which generally build a bus around its sensors, are one such example, as are other spacecraft for military applications. Notwithstanding, for the vast majority of cases the benefits far outweigh any penalties.

PROCESS FLOW

The creation of spacecraft on short notice (responsive) necessitates the existence of a well-established infrastructure. This infrastructure may be based on several approaches: from the pre-built system sitting on a shelf, to the (more desirable) one of having components in a "warehouse" ready to be

integrated to suit. The latter approach lends itself to the greatest degree of flexibility, as modular components may be chosen all the way from the chip level to the box level for a truly unique application every time. Figure 2 shows the high-level process behind MR² spacecraft. First, a need is identified and a request for action is issued to the MR² team. The space system concept is next defined within a virtual design environment, where the mission objectives and the requirements are fine-tuned to develop an operations concept and a spacecraft design. The design also generates an inventory list of required parts and components, which can then be accessed at a "Spacecraft Depot" (SD). Whether the system Integration and Test (I&T) takes 7 days or 12 months depends directly on whether the application sensor (instrument) is sitting on a shelf, is provided by the user, or needs a "special order". In the short end of the spectrum, the spacecraft would be ready for launch vehicle integration and launch within 7 days.

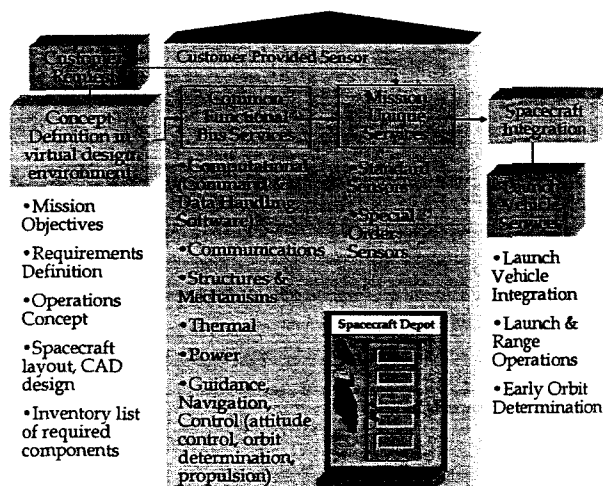


Figure 2: MR² Spacecraft Process Flow - The Spacecraft Depot

The physical location of the SD is still a question that needs to be worked out. Proposals range from a distributed, virtual SD with components maintained at various manufacturer's sites, to a centralized warehouse. Its final implementation would depend on the need for quick access to all components, versus the market drivers of supply and demand. Clearly, 7-day responsive systems would benefit from a centralized location. This model would not be much different from the one used by individual projects today, which acquire parts in quantities and store them as spare parts. The idea would be to extend this practice to creating a "super project" (in fact a *Program*), capable of servicing more than just one mission need.

KEY DESIGN RULES

MR² spacecraft incorporate plug-and-play interfaces. Significant process improvements in life cycle can only be achieved if such interfaces are agreed-upon in advance (standard). For standard plug-and-play interfaces, integrating and testing spacecraft may not be too different than putting a personal computer together, primarily from the electrical and software points of view (with appropriate standard form factors and existing application-level software). Mechanical (including thermal) and fluid interfaces require standardization as well, and examples from the automotive industry or others may be brought to bear. A generic architecture symbolizing this approach is represented in Figure 3. Each element within a functional area may be removed and replaced by another with varying performance levels. Attitude control and navigation sensors and actuators may be replaced as needed without affecting the architecture, much as peripherals and components are added to personal computers to increase or change their performance (more memory, faster drives, wireless communications, etc.).

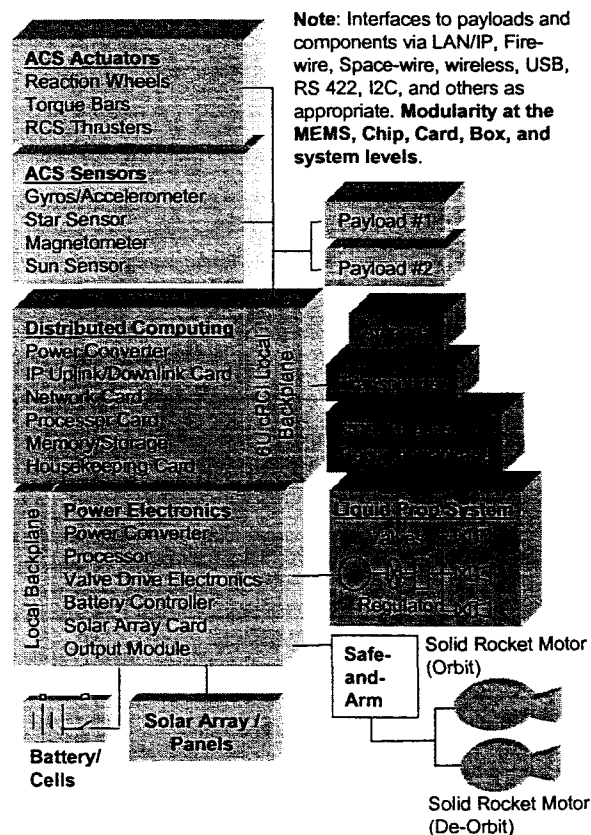


Figure 3: Generic MR² spacecraft architecture

The basic design philosophy is summarized as follows:

- MR² spacecraft must take advantage of multi-billion dollar industry standards for *manufacturing, computing, and communications* technology.
- The *Modular design architecture* must be capable of *evolving* along with technology advances.
- Standardization is implemented at the interface, *not* at the subsystem or system level. Electrical interfaces should use commercial standards, such as Fire Wire, Ethernet, USB, and others. Mechanical and fluid interfaces should also be standard and flexible enough to accommodate various layout configurations. Specialized interfaces for the space industry will be developed *only if required* for a particular set or sets of applications.
- *Choice technologies* (not standard) may be incorporated, with a list reviewed and updated at regular intervals to maintain technological relevance.
- The system will use a commercial, *open code* operating system (i.e., Linux). This enables the incorporation of a common, flexible operating system that encourages industry involvement and stimulates inter-operability among different providers.
- Components would attach via standard interface much as peripherals attach to a computer. Each "peripheral" would need to come with its software driver. The driver is either pre-loaded in the operating system, or loaded as needed by the user.
- The flight software will be based on a layered architecture, with maximum re-use of infrastructure and application modules.
- Communications and information exchange directly from the user to the spacecraft through a *distributed* internet-based payload operations "center". The ensuing architecture calls for the use of spacecraft as point extensions on the Internet.

POINT DESIGN: RSAT

In April of 2003, the IMDC carried out its first design exercise on the MR² paradigm. This first exercise resulted in a preliminary design for a responsive-space geared microsatellite, RSAT. Although both military and civilian-application spacecraft point designs were developed, the results used the same modular components (i.e., MR²). The following paragraphs describe in more detail the civilian application.

Requirements Definition: Scenario

The exercise goal was to design a micro-satellite to observe a particular volcanic eruption in Alaska's Aleutian Islands. The timely and concerted observations are required as this is an important route

for commercial aircraft, affected by volcanic ash. The spacecraft were to continue to monitor the Aleutians over a period of one to two years.

The mission specifications are broadly described in the following technical terms:

- 2 meter panchromatic, 4 meter multi-spectral Ground Sampling Distance.
- Image acquisition at a rate of once every 99 minutes (a constellation of RSAT spacecraft would be needed for this repeat rate).
- Sun-synchronous orbit with altitude of 705 km and inclination of 98.21 degrees.
- Attitude control ~ 1.2 asec, knowledge ~ 0.3 asec, jitter ~ 0.07 asec. Geo-location to within 100 meters. Maneuver capability for 15-degree off-nadir targets.
- Study the interaction of volcanic ash with the upper ionosphere.
- Transmit data directly to the USGS in Anchorage, Alaska
- Data requirements: Scene = 256 Mbits (16 x 16 km frame), Extended = 23.8 Gbits (6% of orbit). Totals include optical and plasma vector data.
- Mission lifetime 1 year minimum, 2 years maximum
- Launch Vehicle Options: Peacekeeper-class

The core spacecraft layout is presented in Figure 4. Its design is consistent with the MR² paradigm, and can satisfy equatorial-to-sun-synchronous orbits with judicious application of modular components.

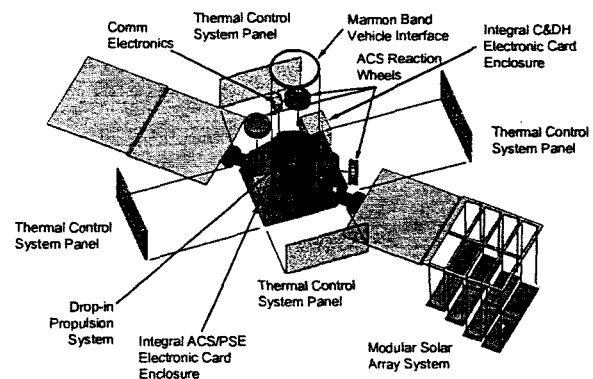


Figure 4: RSAT is a MR² spacecraft

The core structure concept may change depending on mission needs. One possible incarnation is shown in Figure 5. The key is not to marry to a particular design or configuration, but to have structures that can adjust to varying requirements. As MR²

spacecraft are resource-scalable, their structure must also be able to morph accordingly.

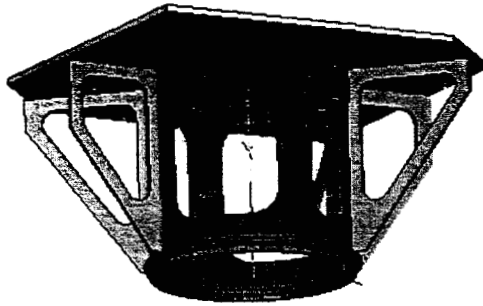


Figure 5: RSAT's core structure satisfies the MR² paradigm

The launch vehicle varies depending on requirements. Although the current point design fits within a Pegasus or Peacekeeper, it may be flown in other vehicles as secondary payload (Figure 6). A constellation may be in place on short notice, compared to today's capabilities.

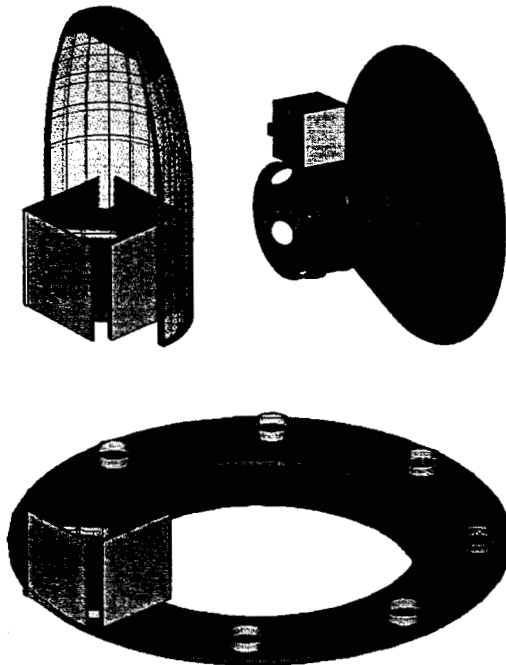


Figure 6: RSAT may fly as a primary payload, or as secondary payload in a host of vehicles.

CONCLUSIONS

The development of MR² as a paradigm shift in the way space systems are put together is a central element of responsive space systems. Nonetheless, MR² is broader in application and scope, as spacecraft

developed under this paradigm are also resource-scalable. From micro-satellites to large spacecraft and systems ("responsive" or not), MR² promises to change the way we design, build, test, and launch space systems. The TacSat series of spacecraft represent an excellent opportunity to inject MR²-compatible technologies into operational satellites. Continuing collaboration between US Government organizations and industry is essential in ensuring this paradigm satisfies its stated objectives. The end result is the ability to significantly reduce costs, and provide a capability that is both in-tune with national defense, and aligned with NASA's Exploration and Scientific objectives.